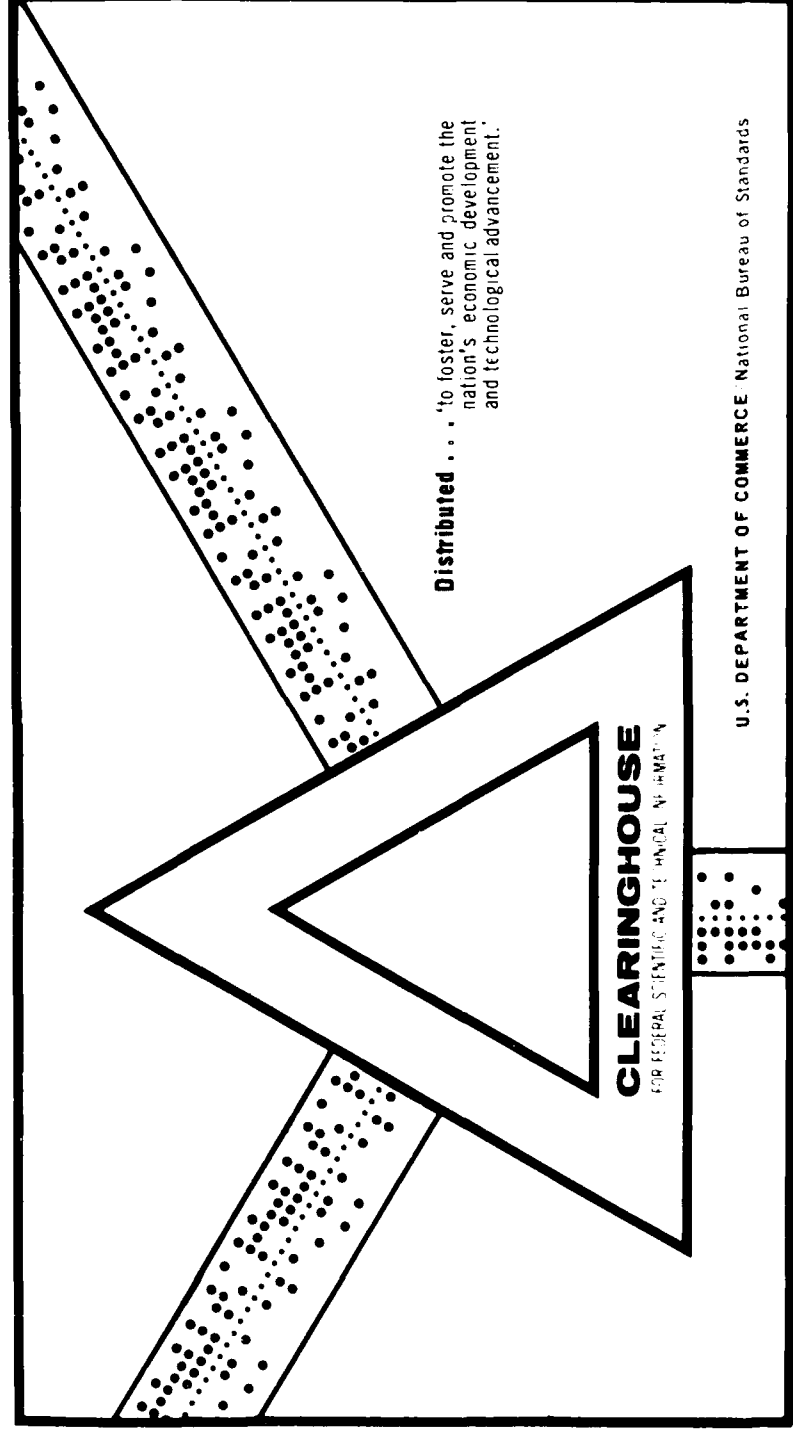AD 698 449

THE EVALUATION OF EXPERIMENTAL FABRICS AS ALTERNATIVES FOR STANDARD WOOL FABRICS

Norman R. S. Hollies
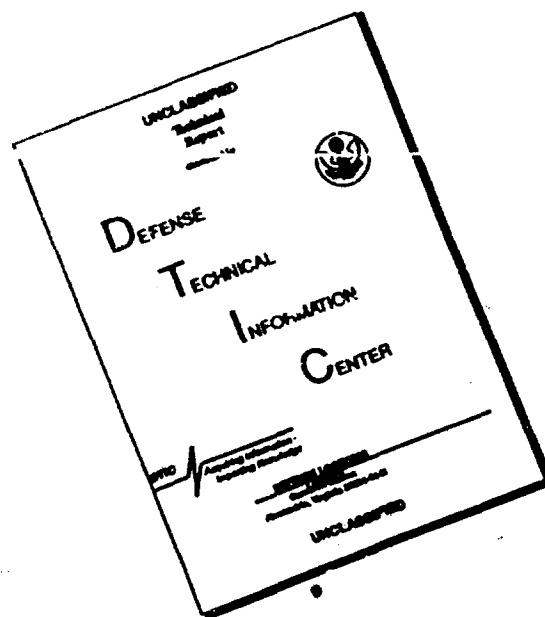
Harris Research Laboratories
Washington, D. C.

December 1955

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

HARRIS RESEARCH LABORATORIES, INC.
1246 Taylor Street, N.W.
Washington 11, D. C.

Report No. 18

Quarter Ending December 25, 1955

THE EVALUATION OF EXPERIMENTAL FABRICS AS
ALTERNATES FOR STANDARD WOOL FABRICS

Norman R. S. Hollies

Contract No. DA-19-129-qm-331

Project No. 7-93-18-018B
Development of Alternate Fabrics to Conserve Wool

* * * * * * * *

SUMMARY

This report is based on a Quartermaster discussion of the problems of comfort in Army cold weather clothing held in Washington in connection with this project on December 1, 1955. In addition to a review of the status of the work on heat and moisture transfer, new experimental data obtained this quarter were discussed and are presented herein.

The comfort aspects directly connected with thermal protection from the cold were considered in terms of: (a) the present multilayer cold weather ensemble in which the fabric layers are of the water vapor permeable type, and (b) possible new cold weather systems in which water movement in the clothing

assembly is restricted by placing a water vapor impermeable membrane in the clothing layers.

The present clothing ensemble, containing many layers for low density and for thickness and used with a wind-proof outerlayer, is an effective thermal barrier to radiative, convective, and conductive losses under most dry cold stress conditions. However, the condensation of moisture in the layers of the assembly from the sweating of an active soldier can substantially decrease its insulation which may then offer inadequate protection while the same soldier rests. Moisture collects in the layers of the fabric assembly largely by distillation from one layer to the next. The amount of water distilled can be reduced somewhat by using hairy-surfaced fabrics of low surface wetness and in this way the fabric properties of the individual layers can have an effect on the insulation of this type of cold weather garment ensemble.

The movement of water vapor in clothing may produce another thermal effect important to comfort in clothing which is derived from the hygroscopic nature of the fibers which are used. The heat (of regain) produced when clothing in equilibrium with a warm-dry (indoor) atmosphere is exposed to cold-wet (outdoor) conditions may be important to cold weather protection. A laboratory technique has been developed to measure this effect from the temperature rise in fabrics exposed to humidity changes and shows promise for evaluating its importance under the moisture and thermal gradients present in clothing assemblies.

Practical cold weather clothing systems must allow heat to dissipate easily when the soldier is active and insulate well when the soldier rests. Evaporative cooling as a mechanism for heat removal is shown to be relatively unimportant in laboratory experiments with the present cold weather clothing ensemble. Body

motion, however, may be a factor in forced convective cooling of the active soldier, but this process has as yet not been subjected to a thorough study under controlled conditions.

Cold weather clothing assemblies employing a water vapor impermeable layer (and especially when placed near the skin) have shown improved insulation properties to wet-cold conditions in both laboratory and field work. The impermeable membrane acts mainly to reduce moisture transfer to the insulating layers and thus their thermal resistance is maintained. This change in cold weather assembly design also results in reduced ability to dissipate heat so important when the clothing is worn by an exercising soldier. Laboratory tests simulating cold exposure have shown that the use of impermeable membranes with holes may result in increased insulation with this type of assembly in a chilling experiment, without increasing the heat stress problem during activity. Other studies have indicated that moisture collected in the fabric layers over holes in the vapor barrier membrane is not transferred laterally along the rest of the layer and so good thermal insulation is maintained after moisture distillation ceases. This type of clothing design is now being evaluated in the field under cold stress conditions. Other designs to relieve the heat stress problem in cold weather clothing appear possible and will be examined in further laboratory and field tests.

COMFORT PROPERTIES IN COLD WEATHER CLOTHING

TABLE OF CONTENTS (Continued)

DETAILS

COMFORT PROBLEMS IN COLD WEATHER CLOTHING

I. Introduction

A. Basis for the Report

A discussion of the status of problems of comfort in Army cold weather clothing was held in Washington on December 1, 1955. Representatives of the Textile Clothing and Footwear Division of the Natick Quartermaster Research Center and of Harris Research Laboratories were participants. The discussion centered around a review of the present concepts of comfort in cold weather clothing based on information from laboratory work done in both laboratories, on physiological and field studies, and on data in the literature. This material included some new work on cold weather clothing problems obtained in this research project during the past quarter. The scope of the present report has been expanded to include a written record of the material that was covered at this meeting and includes, where possible, the sense of the comments made by those taking part. Credits for information obtained from the work of other laboratories are given in the appropriate tables and figures of the report.

B. Purpose of the Discussion

The material presented was directed at reviewing the present state of our knowledge of the principles involved in the design and performance of cold weather combat ensembles with special attention being paid to the subjects of thermal insulation and moisture transfer. An attempt was made at each point in the discussion to obtain the answer to two very important practical questions:

(1) How can the knowledge that has been gained be best applied to improving cold weather clothing for the soldier?

(2) What areas of work required further clarification and how can problems in these questionable areas be examined in a realistic way?

C. Nature of the Discussion

The principles of thermal protection can be examined in terms of the paths of heat transfer in realistic garment assemblies. Two main classes of assemblies have been extensively studied:

(1) The conventional multilayer cold weather ensemble.

(2) Ensembles employing a water vapor impermeable layer.

The thermal protection principles for each ensemble type will be discussed separately.

II. Transfer of Heat and Moisture in Cold Weather Clothing

A. Conventional Multilayer Cold Weather Ensembles

1. Definition

Generally, the cold weather ensemble for use in cold-wet environments consists of several fabric layers -- underwear, serge or shirting, frieze with liner, and a field jacket. This fabric system is sometimes referred to as belonging to the vapor permeable class because all of the fabrics involved in the assembly are individually permeable to the passage of water vapor. The most important feature of this ensemble is its multilayer nature, which gives it great flexibility in terms of body movement of the soldier and good adaptability for thermal protection, since the number of layers that are worn can be varied to suit different exposure and activity levels. In terms of the various paths of heat loss, the action of this assembly type is probably quite well understood. A quick review of these will serve to point out what features of the assembly

- 3 -

design are most important for cold weather insulation.

2. Paths of Heat Loss

(a) Radiation of heat from the clothed soldier to a cold environment depends mainly on the relative temperatures of the two as related in the Stefan-Boltzmann Law

$$H_{radiation} = S_o e_1 e_2 (T_1^4 - T_2^4)A$$

in which S_o is a constant, e_1 and e_2 are the emissivities of outer clothing and environment, T_1 and T_2 are corresponding temperatures, and A is the area of radiation. In a cold environment, this heat loss is usually small because most of the temperature drop between body and environment occurs within the many clothing layers. In addition, the absolute values of T_1^4 and T_2^4 are not large at low temperatures. Actually it is experimentally difficult to separate radiation losses from those by other paths and so they are often included in convective loss figures as indicated below.

(b) The main convective heat losses from a clothed man are those caused by exposure to wind in the cold. As is shown in Table 1, thermal insulation of a clothing system can be maintained only if the outer layer limits penetration by the wind. Coverings with air permeability values of about 12 ft^3/min ft^2 or less appear to result in good protection from wind penetration. This principle has been incorporated into the conventional cold weather ensemble by using a tightly-woven sateen outer layer.

Wind acts in a second way to increase convective heat loss from a clothed man. The still air layer which normally clings to all objects and adds to their insulation value, is blown away even in a moderate wind. This is shown in Table 1, where loss of insulation of the assemblies protected by an outer

layer of very low air permeability was at least 0.01 $m^2hrC°/kcal$. A clearer
view of the extent of this effect over a wide range of wind velocities is given
by the physiological data for losses from the body shown in Figure 1. Efforts
aimed at maintaining the insulation advantage of the surface air layer by
change in the surface character of the outer fabric of a cold weather ensemble
have not received much attention in cold weather garment studies. However, this
is an area in which possible improvements could be made in the present cold
weather ensembles, if other functional requirements were not adversely affected.

(c) The reduction of underline conductive heat loss has received perhaps the most
attention in connection with clothing improvements. Insulation in single layers
has been correctly attributed to the actual amount of poorly conducting air held
within the fabric. Thus, from a great variety of laboratory testing, increased
thickness and decreased density in cold weather garments have been an established
goal for improving cold weather protection. There is also good evidence from
field tests that this has been a proper goal, and an example is given in Table
2. In this instance the length of time a soldier could tolerate extremely cold
conditions depended quite critically on the thickness of the underwear used in
this cold weather ensemble.

The use of many layers of fabrics has been a very practical means for obtain-
ing a thermal insulating assembly of low density. The importance of the air
space between the fabric layers has been confirmed recently in a rather elaborate
thermal study of a variety of fabrics, the results of which are shown in Figure
2.

However, the insulating value of cold weather ensemblescannot be fully
predicted from studies of the thermal insulating value of the dry fabric alone.

Because moisture is important in cold weather insulation, the behavior of garments containing water must also be considered.

3. Moisture in Cold Weather Clothing

(a) Sources of Water in Clothing

In the use of cold weather garment assemblies, water, a good thermal conductor, may penetrate the insulating region from rain or snow on the outside and from body perspiration on the inside. Outside penetration of the conventional multilayer assembly has been limited for most environmental situations by using a water resistant outer layer. The reduction of moisture penetration from sweat secretion poses a number of comfort questions, only some of which have been answered for the multilayer cold weather system but which, nonetheless, are important in determining which ensemble is ultimately most satisfactory. These problems may conveniently be approached by first considering the physiological requirements for protecting a person in the cold and then by determining the types of fabrics or ensembles best suited to meet these requirements.

(b) The Anomaly of Heat Stress Caused by Cold Weather Clothing

The metabolic heat production of a soldier may vary from 50 kcal/m^2/hr while resting to 500 kcal/m^2/hr while very active. The use of sufficient insulation to maintain his body temperature while resting may impose a heat stress on him while active. Thus, studies aimed at improving the overall insulating effectiveness of cold weather clothing must take into account the possibility of heat stress under conditions corresponding to high metabolic activity. In addition, in the situation in which a soldier is active and hence sweats and then is forced to be inactive in the cold, there is an appreciable loss in thermal

insulation of his protective ensemble because water appears in the clothing layers. Thus, in the development of new types of cold weather clothing, it is important to be able to examine the systems under conditions which at least simulate the two important physiological stress situations: heat stress due to "overclothing" at high metabolic activity and chilling due to devaluation of the insulation by perspiration.

(c) Cold Weather Clothing Testing in the Laboratory

A laboratory method, which simulates the stress conditions described in the previous section* has been developed for obtaining the insulation properties of cold weather clothing fabrics. The samples are wrapped around a "simulated sweating arm" whose heat output/unit area can be varied to match the metabolic output of the body. The clothed arm is placed in a cold chamber in which temperature and wind velocity are controlled.

Experiments on cold weather clothing are carried out in two phases:

(1) For a fixed period of time the arm is supplied with heat (electrically) in sufficient quantity to keep the skin at a normal physiological temperature. The amount of heat supplied is sufficient to cause the cell to sweat heavily and transfer moisture to the clothing and is also a measure of the ability of the cold weather assembly to dissipate heat under high metabolic rate conditions.

(2) The heat input of the arm is then lowered to a value which would correspond to a low metabolic rate and the arm is allowed to cool in the cold wind stream. From the rate of cooling, the overall insulation of the assembly can be calculated.

＊＊＊＊＊＊＊＊＊＊＊

* For a full description of this method, see quarterly reports no's 11, 13, and 15, Contract qm 564.

Two other types of information are available in these cold wind tunnel experiments:

(1) The weight of water in each layer can be obtained, indicating how much moisture has been transferred from the sweating skin.

(2) The thickness of the wet fabric layers can also be measured, which is useful for establishing the relative insulating value of each component of the assembly.

Studies of the cold wind tunnel type have proved useful for examining the ways in which moisture collects in layers of cold weather ensembles and, as will be shown later, have made it possible to select at least some of the fabric properties most important to good cold weather insulation.

(d) Moisture Collection in Clothing and Its Effect on Insulation

Four layer cold weather assemblies of the present multilayer type were examined using the cold wind tunnel technique. The increase in moisture content of each layer of a typical assembly exposed for different periods to the hot sweating conditions is shown in Table 3. The three inner layers picked up 15 to 40% moisture above their initial equilibrium value (70°F., 65% R.H.), the inner layers gaining water more quickly than the outer layers. This general type of behavior was observed for all the cold weather ensembles studied irrespective of the properties of the component fabrics.

The thermal insulation values of the same assembly as a function of this "exposure time" to heavy sweating conditions are shown in Figure 3. From these data it can be seen that, while transfer of perspiration moisture to the fabric layers was not large (Table 3), it produced an appreciable loss in thermal insulation in these cold weather ensembles. After 25 minutes of "hot sweating"

LIMITED USE DOCUMENT

activity on the simulated arm, the subsequent insulation of the assembly in the
cold dropped below that for a two layer "dry" fabric assembly. The fact that
the total amounts of moisture collected were not large and that the build up
with time was so slow suggested that water was not passing through the fabric
layers in liquid form, and so the mechanism of transfer was examined separately
in a simpler type of experiment.

(e) The Mechanism of Moisture Transfer in Clothing

Experiments were carried out in which various dry serge fabrics
were placed in contact with wet underwear fabrics as would be the case in cloth-
ing on a soldier after a period of heavy activity. Moisture gain by the serge
fabrics as a function of time was measured with and without a temperature dif-
ference between the fabric layers. Experimental results are given in Table 4.

It was interesting to find that, when the fabric layers were kept at the
same temperature, only a little more moisture than that corresponding to satura-
tion regain was passed from the wet underwear to the dry serge layers. There
was no tendency for wicking between the layers by a capillary process. In the
corresponding experiments in which the underside of the underwear was warmer than
the top surface of the serge, more water was transferred, which increased appreci-
ably as the time of contact was lengthened. This behavior indicated that moisture
was being transferred across the small air gap between the layers by a straight
distillation process. Consistent with this mechanism was the finding that the
rate of moisture transfer could be calculated from the vapor pressure differentials.
The distillation mechanism was found to hold over a wide range of applied pressures
and fabric types and even when the wet underwear was placed over the serge. Wick-
ing of water between the layers occurred only if the contact pressureswere well

- 9 -

above usual garment pressures (1.0 lbs/in^2 compared with 0.01 lb/in^2) and the underwear used was sopping wet.

For temperature gradients between the underwear and serge layers of the same magnitude as those found in cold wind tunnel experiments, the amounts of moisture collected were similar to those of Table 3. This indicated quite clearly that moisture distillation between the layers rather than wicking in the capillaries formed by the fibers was the controlling moisture transfer process in the cold weather clothing situation. The driving force for moisture transfer thus arose from the differences in water vapor pressure in the fabric layers resulting from the difference in temperature between the sweating skin and the environment.

(f) Fabric Properties Important to Moisture Transfer in Cold
     Weather Clothing

Experiments of the two layer moisture transfer type were examined more closely to see if there was any specific effect due to the nature of the fabrics employed. As is shown in the data of Table 4, moisture transfer to the Orlon serge, under the influence of a temperature gradient, was larger in all cases than to the wool serge fabric in the same period of time. These serge fabrics, however, were known to differ in a number of other fabric properties which would conceivably affect moisture transfer in a distillation process. In a series of controlled experiments in which the water transfer to pairs of fabrics differing only in surface hairiness or fabric wetting behavior was studied, the following observations were made:

(1) Smooth surfaced serge tended to collect more water than those with fuzzy surfaces, presumably because of the closer contact and hence shorter

- 10 -

distance between the evaporating and condensing surfaces. For the fabrics compared in Table 4, the Orlon serge, which collected more water, also had the smoother surface.

(2) As water was collected by the serge materials some developed a wet appearance before the others and this behavior coincided with a high rate of water collection. Apparently the film of water forming on the fabric surfaces in these cases again had the effect of decreasing the total distance over which distillation had to occur, leading to a greater transfer of water. Fabrics of this type were said to have high surface wetness and generally they were also the most easily wet of the group studied. For the serge pair in Table 4, Orlon was of this class, so perhaps gained more water than the wool serge for this reason as well.

(3) It was observed in moisture transfer experiments on another group of serge fabrics that those containing high regain fibers tended to gain water more quickly than the low regain materials in the early stages of the moisture transfer process. However, at moisture content figures above that for saturation regain for these materials this effect was no longer observed.

It was apparent, from this study of the fabric properties important to the process of water transfer in garment assemblies, that a clearer definition of the wetting properties of fabrics was necessary. As a first step it was observed that under the experimental conditions of Tables 3 and 4, water was not transferred by capillary action between the fabric layers of an assembly, so the "wicking" properties, per se, of the fabrics were not involved. On the other hand, it was observed from moisture transfer studies that separation of the fabrics into wettable* and non-wettable groups corresponded in all cases studied to fabrics

* * * * * * * * * * *
* As determined from the rate of penetration of the fabric by a drop of water - relatively rapid penetration defining fabrics as wettable.

exhibiting high and low surface wetness respectively. However, within the wettable group, the degrees of surface wetness varied considerably. This last observation has pointed to the need for a better experimental definition of surface wetness, and this is proposed as an area for further research.

Moisture transfer experiments have thus shown that the surface hairiness and surface wetness properties of fabrics may materially alter the rate of water transfer between fabric layers differing in temperature as they would when worn as clothing layers. This is true because water transfer occurs by distillation rather than by wicking in these fabric assemblies under at least static contact conditions. Preliminary work on the rates of moisture transfer between moving fabric layers have indicated that moisture movement in clothing used under dynamic conditions would still be by distillation. However, this whole area of cold weather clothing evaluation under simulated stress conditions needs further consideration.

(g) Moisture Transfer and Thermal Insulation

The thermal behavior and moisture distribution in several cold weather garment assemblies of comparable thickness were studied using the cold wind tunnel technique, the results of which are shown in Figure 5. In these particular experiments the fabrics were exposed to sweating conditions for 30 minutes with a skin temperature of 30°C. and then allowed to cool in the wind stream at -5°C. Moisture contents of the layer were obtained after the simulated arm had stopped cooling. Underwear and serge layers were specially chosen so that their wettability could be varied while keeping fiber content and surface hairiness properties constant. A nylon underwear (#62) was used for comparison with a water repellent treated sample (#65). A sheared wool serge (#17SH) and

- 12 -

a wool serge (#17TR) treated with wetting agent were also used.

The effects of using wettable and non-wettable nylon underwear and serge layers were somewhat more complicated than in the two layer system. In general, moisture content of the layers was lowered by replacing the wettable underwear with a non-wettable type (Case 1 and Case 2), as would have been expected from the work on two layer assemblies. However, with both underwear and serge of non-wettable material (Case 4), the moisture content of the insulating serge layer remained high. This result could be explained as follows: Although the rate of distillation of water into the serge layer had been decreased, the rate of distillation out of the serge layer was also lowered as indicated by the relatively low moisture content of the jacket liner. Thus, the moisture content of any one layer in these cold weather assemblies appeared to depend on the relative rates of distillation of water into and out of that layer as affected by the fabric surface properties.

One feature was common to the results for all of the assemblies in Figure 5, i.e., they all collected some water from the sweating cell. Hence, although the overall thermal resistance values of these assemblies were lowered in proportion to the moisture contents of the layers, the final insulation values were quite similar for all of the cases. With other cold weather garment assemblies in which quite different first and second layer fabrics were used, the results were very similar. In addition it was found that the effects of fabric thickness on the total insulation of the wet assemblies followed the same general pattern as with any systems (cf. Figure 2), thermal resistance being proportional to total thickness.

Thus, in these special cold wind tunnel studies in which assemblies containing

fabric layers of controlled fiber content and surface properties, but with different wetting properties, were used:

(1) The surface wetness, not the fiber content, of the fabric layers was found to alter the water content of each layer.

(2) Thermal resistance of the assemblies was found to be proportional to the total moisture content of the layers but, for assemblies of comparable thickness, the overall insulation values were quite similar.

(h) Heating Effects Due to Movement of Water in Clothing

Due largely to the efforts of A.B.D. Cassie of the Wool Industries Research Association in England, it has been clearly established that fibers moved from a warm-dry atmosphere (winter, indoors) to a moist-cool atmosphere (winter, outdoors) do pick up moisture. The moisture gained liberates heat and, because this moisture is essentially proportional to the regain value of the fiber, the effect has been called the "heat of regain". Actually heat is liberated from water sorbed on the fiber surface and from the condensation of water in the submicroscopic fiber capillaries. From the regain figures for the different fibers in equilibrium with warm-dry and cold-wet conditions, the amount of water picked up can be calculated as is indicated by the third line of Table 5. From the heat of fiber wetting (Q calories/gram) and the heat of condensation of water (L calories/gram), the total heat of sorption or "heat of regain" (L + Q) can be obtained. Multiplied by the amount of water collected on the fibers, the total heat of regain (per kilogram in Table 5) can be obtained. For a multilayer clothing assembly weighing several kilograms, it is easily seen that the total amount of heat involved is equivalent to a large fraction of the body heat produced in an hour.

- 14 -

It has never been clearly established that such heating contributes, in fact, to comfort in cold weather ensembles. The difficulty lies in determining how much of the heat goes to warm the body and how much is dissipated to the atmosphere. In addition, the time taken for the heat to distribute itself in a clothing system may also be critical. For example, distribution of this amount of heat throughout the clothing over a period of an hour might conceivably be quite effective while a sudden heat pulse of this magnitude could contribute to heat stress if the body were already warm and active in a cold weather assembly.

The results of recent efforts to evaluate this effect from the temperature rise of fabrics subjected to changing conditions are summarized in Table 6. In this work, two layer fabric assemblies (serge and underwear) were conditioned at one realistic environmental condition. Temperature rises between the fabric layers were noted. In each experiment in Table 6, a pair of fabric assemblies were run together, in which a single variable - ambient condition or fabric type - was examined.

For Run R_2, in which one assembly was dried more than the other, no difference in effect could be observed when the fabrics were placed in a cold atmosphere. On the other hand, with a napped serge as the outer fabric, placing of the nap toward the underwear layer had some effect on the rate of cooling of the assembly even though the starting conditions were the same. Thus, the length of the diffusion path for water vapor entering the body of the fabrics had some influence on the total heating effect obtained. As would have been expected from the data of Table 5, the wool serge in run R_7 gave a noticeably greater increase in temperature than that for the Orlon serge in similar transfers at room temperature Experiments were also made (W248-W253) to determine whether a heating pulse would

- 15 -

be developed if a dry fabric were placed on a warm sweating skin. Here again the system containing a wool fabric gave a slightly greater temperature rise than the one with Orlon, although neither effect was very large. In runs R11 and R12 the temperature rises in each assembly were measured and, for these environmental conditions, the assembly containing wool produced a significantly greater temperature rise than the one containing an Orlon serge. The data for run R12 are given in Figure 4, showing the extent and duration of the temperature rise in these assemblies above room conditions. For one of the cases (R11), that for transfer from 32°C., 20% R.H. to 32°C., 90% R.H., the actual heating in the assembly, measured by using an electrical analog device*, amounted to 150 kcal/m^2/hr for the hygroscopic wool system. As a man walking would produce approximately this amount of heat in an hour, it is clear that the total effect due to heat of regain could be quite important in some situations. The method for evaluating the extent of the heating effect within the clothing layers appears quite promising and will be extended to include more realistic four and six layer cold weather clothing systems under a variety of environmental conditions.

      (i) Cooling Effects Due to Movement of Water in Clothing

While evaporative cooling at the skin has been widely discussed as a means for alleviating heat stress of active soldiers in cold weather clothing or of contributing to chilling during inactive periods, the evidence from laboratory studies does not appear to support this view. In the first place the

* * * * * * * * * * *

* This method for evaluating the heat of regain effect will be reported in some detail in the next quarterly report

LIMITED USE DOCUMENT

water vapor resistance of these assemblies is high as shown by the calculations from values for single layers given in Table 7. Secondly, the total amount of water which can be passed through a cold weather assembly under realistic temperature gradients between the fabric layers is quite limited. This can be seen from Table 8, in which the moisture loss for a temperature distribution obtained in cold wind tunnel experiments has been calculated. Hence, even if all of the heat of evaporation of water went to cool the body of an active soldier, heat stress would be imposed, and this indeed has been observed in actual physiological tests.

It has been suggested that body motion in a high activity period leads to a bellows action in clothing layers and that this results in a forced convective cooling of considerable magnitude. This is certainly an area for possible improvement in cold weather clothing which deserves further attention.

Actually evaporative cooling for an active man dressed in the conventional cold weather ensemble is probably most effectively achieved by direct exposure of the skin or inner fabric layers to the environment. Some indication of the required area of exposure is shown by the simulated sweating arm data of Table 9. In this instance only slight exposure of the skin to the atmosphere resulted in greatly increased cooling of the sweating arm.

Thus this work has indicated that evaporative cooling in cold weather systems may not be a very important heat loss mechanism under static conditions. However, the extent of heat loss by this mechanism for a clothed moving body still needs critical examination. The laboratory approach has also shown that very effective evaporative cooling is possible if some direct skin exposure is achieved in apparel clothing. It may be quite important to consider this fact in

- 17 -

the design of cold weather clothing systems where effect.ve cooling gaps are

required to relieve heat stress of the active wearer.

. 4. A Summary of Comfort Factors in Conventional Multilayer Cold

Weather Ensembles

The multilayer fabric assembly employing thick, low density fabrics is

most effective as an insulating system against dry-cold conditions and, when a

wind proof outer layer is used, remains effective even in high winds. However,

the use of water vapor permeable fabrics for the individual layers of the assembly

cannot prevent water from condensing in the insulating regions when such an

assembly is worn by an actively engaged, and hence sweating, soldier. Such

condensation of water leads to only a slightly increased amount of evaporative

cooling and results mainly in loss of insulation due to filling of the fabric air

space with water. Hairy surfaced fabrics of low potential surface wetness appear

to be effective in slowing down the distillation of water from layer to layer in

cold weather garment assemblies. However, because the condensation of even only

a small amount of water in the main insulating layers results in decreased in-

sulation, protection of a resting soldier may, in this way, become inadequate

for many environmental stress conditions.

Fabric systems can be designed which restrict the motion of water vapor into

the insulating regions of cold weather garment assemblies and these systems will

be considered in discussion of the second class of cold weather clothing.

B. Cold Weather Ensembles Employing a Water Vapor Impermeable Layer

1. Effects of Using an Impermeable Layer for Complete Body Coverage

(a) The Vapor Barrier Effect on Moisture Transfer

Cold wind tunnel experiments were carried out on several four

- 18 -

layer cold weather ensembles in which a thin polyethylene film was placed between the layers to limit moisture distillation. The results for experiments on one of these assemblies, in which the impermeable film was placed between different fabric layers, are given in Figure 6. As in the previous work, the fabric assemblies were held for 30 minutes at a skin temperature of 30°C. and allowed to cool to equilibrium in a wind stream at -5°C. Water contents of the fabric layers were obtained after completion of each experiment.

As can be seen from Figure 6, moisture transfer to the insulating layers was greatly changed by incorporating an impermeable layer into three of the four assemblies. Not only was moisture not transferred to fabric layers beyond the membrane but these fabrics, cut off from a moisture source, lost some water to the windstream, as indicated by the negative water content figures.

(b) The Effect of Vapor Barrier Position

Placement of the impermeable layer near the sweating skin or underwear in these experiments resulted in a substantial increase in overall insulation of the assemblies (compare Case 1 and Case 2 with Case 4). In the experiment in which the moisture impermeable layer was placed within the field jacket (Case 3), neither the moisture distribution in the fabric layers nor the insulation value of the assembly was noticeably altered (in comparison with the no barrier Case 4). This behavior could again be attributed to the high water vapor resistance of the whole assembly (cf. Table 7).

(c) The Water Vapor Barrier Effect in Physiological Tests of Cold Weather Assemblies

A review of the Climatic Research Laboratory work of 1944 on cold weather assemblies containing a water vapor impermeable layer indicated

thermal insulation behavior similar to the laboratory findings of Figure 6. The factual information recorded from some of these physiological tests is summarized in Table 10.

In general, it was found that water vapor barriers worn next to the skin (in the case of sockgear) or on the inside of the main insulation region (in the case of sleeping bags) gave a measurable improvement in cold weather protection. On the other hand, vapor barriers placed on the outside of the assemblies (for sleeping bags and field trousers) had no detectable influence on the overall insulation of these assemblies. In one case (that for sleeping bags), there was no difference in the increase in weight of the bag with or without an impermeable outer layer, indicating again the influence of the high total water vapor resistance of these assemblies.

2. Partial Coverage by Impermeable Membranes - A Cold Weather Clothing Modification

(a) The Heat Valve Requirement for Cold Weather Clothing

Although the use of a water vapor barrier appears to be very effective in increasing the insulation of cold weather assemblies, it has the weakness of lowering the heat dissipating capacity of an assembly which is so important when used on an active wearer. Thus heat stress may be quite severe in assemblies in which no water vapor at all has been allowed to pass (see reports on the Coldbar uniform of October, 1952, December, 1952, and January, 1953, and the field test of O'Brien, February, 1953).

Hence, a general requirement for suitable cold weather clothing employing a water vapor impermeable layer is that it acts as a type of heat valve which will "allow maximum heat dissipation when the body activity is high but prevent the

LIMITED USE DOCUMENT

condensation of moisture in the main insulating layer so that heat loss is kept
at a minimum when body activity is low."

    (b) Principles of Action of the "Partial Coverage" Cold Weather
         System

         In the laboratory it has been possible to reduce the condensation
of water in the insulation regions of cold weather ensembles, without unduly
lowering the heat dissipating property, by having holes in the vapor impermeable
layer. That this design does indeed increase overall insulation without greatly
lowering the heat dissipating capacity of the assemblies is shown by the cold
wind tunnel data of Table 11. For example, with 93% coverage by the impermeable
layer, a 70% increase in insulation is achieved with only a 16% loss in heat
dissipating capacity.

         There is confirmation to this approach in recent physiological data obtained
on specially prepared Coldbar and regular cold-wet assemblies, the data for which
are given in Figure 7. Both the sweat loss and pulse rate are good physiological
indices of heat stress and, as can be seen from this figure, both were low for
soldiers wearing the vapor barrier Coldbar suit containing 1/8" holes. Indeed,
this uniform, which had 20% less body coverage than the full Coldbar suit,
exhibited less heat stress than either the Coldbar or regular cold-wet multi-
layer assembly.

    (c) Moisture Transfer from Uncovered to Covered Areas of Assemblies
         Containing an Impermeable Layer.

         It has been postulated that cold weather clothing containing a
vapor impermeable layer covering only a portion of the body would become inef-
fective as an insulation system if held for a long period over a heavily sweating

- 21 -

skin. This could occur, for instance, if water "wicked" transversely along the fabric layers after being condensed in the region of the assembly not covered by the impermeable layer.

Moisture transfer experiments of the two layer type were set up to investigate this point and results from a group of these are given in Table 12. As in the previous moisture transfer work, a dry serge sample was placed on a wet underwear fabric and the sandwich subjected to moderate pressure and a temperature gradient realistic for cold weather clothing. In these experiments a sheet of polyethylene covering only one half of the area of contact between the two fabrics was used. After transfer had occurred, the serge sample was cut at the point where the edge of the polyethylene film lay and the two pieces were weighed separately.

Very little moisture was transferred to the serge half protected by the plastic film even with the underwear sopping wet (175%) in contact with a "wettable" serge fabric. This showed once again that "wicking" was not involved in the moisture movement process even along the same fabric under these conditions. Presumably wicking did not occur because the moisture content of the serge section exposed directly to the underwear never reached a high enough value to result in capillary water in the fabric. This at least partially explains why the special cold weather ensembles only partially covered by an impermeable layer were found to have good insulation even after being exposed to a heavily sweating surface (cf. Table 11). Possibly studies on moisture transfer in clothing fabrics of even higher "surface wetness" should be examined using this partial coverage transfer technique.*

* * * * * * * * * *

* For a full discussion of the meaning of the fabric properties of wicking, wettability, and surface wetness, see the earlier section A, 3 (f) "Fabric Properties Important to Moisture Transfer in Cold Weather Clothing."

3. The Design and Testing of Future Cold Weather Clothing Systems

On the basis of the laboratory findings for cold weather clothing containing partial coverage with a vapor impermeable layer (Tables 11 and 12), a feasibility test of this principle is being carried out in the field. Cold weather ensembles with an impermeable layer next to the underwear, but covering different portions of the body, will be worn in Mt. Washington this winter. Efforts will be made to determine the response of men in such an assembly to exercise and sweating conditions and to chilling in the cold. This experiment represents one approach to limit moisture condensation in the insulating layers but without adding to the heat load of the soldiers in the active state.

Other schemes for achieving the best type of heat valve are possible. The "climostat" suit, in which body movement (in a high activity period) can produce internal forced convection and water evaporation, seems to have merit. Another approach might consist of placing flaps in a cold weather suit which were several layers deep so that evaporation of water would not be hindered when the flaps were open and the heat stress tendency could be materially reduced.

In general, the combination of the vapor permeable and vapor impermeable cold weather ensemble types seems to present a promising approach for improved cold weather clothing. Any system which will combine the good thermal insulation and wind protection features of a multilayer assembly with a fabric arrangement for adequate water vapor control is a worthwhile goal for future studies on comfort in cold weather clothing.

The methods for determining the mechanism of heat and moisture transfer in future cold weather clothing studies should also be extended. A means for studying the dynamic response of clothing to moving body conditions, for example,

- 23 -

would be most helpful in evaluating these systems. This is particularly true since the extent of heat loss through a cold weather ensemble worn on an active man involves such a critical region for operation. Another serious gap in our present knowledge of cold weather clothing lies in the area of direct physiological examination of the principles for moisture transfer in clothing already extablished on physical models in the laboratory. Because the fabrics which can be used for cold weather clothing differ greatly in their wet fabric properties due to yarn and fabric construction features, or due in some cases to the type of fiber used, it becomes most important to determine which classes of fabrics are physiologically most satisfactory in cold weather use. In addition, as the Army must be prepared to use different fiber materials in critical periods, it becomes doubly important to know how to put these materials to most effective use. The development of improved cold weather clothing for soldiers probably requires activity at all research levels: in fiber and fabric testing, in laboratory simulation of cold stress problems, in controlled physiological evaluation of the clothing on subjects under cold stress, and in field testing of cold weather assemblies.

TABLE 1, REPORT 18

WIND PROTECTION AND HEAT LOSS[a]

Outer Fabric[b]	Air Permeability[c] $ft^3/min\ ft^2$	Insulation Loss[d] $m^2hr\ C°/kcal$
mosquito net	34.5	.098
rayon twill	21.3	.038
uniform twill	13.3	.025
herringbone twill	11.5	.013
muslin	8.9	.017
poplin	4.0	.017
8 oz. duck	3.8	.008
rubber cloth	0	.007

[a] Climatic Research Laboratory Report 43-A, January 15, 1944.

[b] Over Double Wool Pile.

[c] Frazier Method - impact velocity 32 mph.

[d] Decrease in insulation on increasing wind velocity from 4 to 15 mph (copper cylinder method).

TABLE 2, REPORT 18

TOLERANCE TIME OF TEN SOLDIERS WEARING
ZONE 1 UNIFORM WITH DIFFERENT UNDERWEAR FABRICS
(Exposure at -40°F.)

Underwear Type	Thickness at 0.01 lb/in^2 mils	Tolerance Time[a] min.
none	0	56
50/50 wool/cotton	93	68
double faced wool pile	231	90

[a] From CRL Provisional Report of July 21, 1944.

TABLE 3, REPORT 18

MOISTURE GAIN BY THE INSULATING LAYERS
OF A FOUR LAYER COLD WEATHER ASSEMBLY WRAPPED
ON A WARM SWEATING CELL[a]

(Wind Velocity 12 mph, Exposure Temperature -5°C.)

Exposure Time[b] min.	Moisture Gained by[c]			
	Underwear %	Serge %	Oxford %	Sateen %
0	0	0	0	0
25	37	33	16	5
40	37	42	31	10

[a] Assembly consisted of a 50/50 wool/cotton underwear, an Orlon serge fabric (#20) and the oxford and sateen layers of the field jacket. The warm sweating cell was held at 30°C. with a heat input of 680 kcal/m^2/hr.

[b] To warm sweating conditions.

[c] Above conditioned weight.

TABLE 4, REPORT 18

THE TRANSFER OF MOISTURE TO DRY SERGE FROM UNDERWEAR CONTAINING 100% MOISTURE
CONTACT PRESSURE 0.1 lbs/in^2 - COMBINED EFFECTS OF TEMPERATURE AND TIME

Contact Time min.	Moisture Gained by[a]			
	Orlon Serge (20)		Wool Serge (17)	
	No Temp Diff %	20°Temp Diff %	No Temp Diff %	20° Temp Diff %
10	1.4	10.2	6.0	8.5
20	1.9	20.2	9.8	15.2
30	2.4	29.8	11.9	24.6
40	2.6	40.8	13.0	29.4
60	2.8	53.5	14.6	35.4
100	3.5	64.2	15.6	44.0

[a] Weights in percent above conditioned weight at 70°F., 65% R.H.

TABLE 5, REPORT 18

WATER SORBED AND TOTAL HEAT AVAILABLE FROM TRANSFER
OF FIBERS FROM LOW TO HIGH HUMIDITY

	Viscose	Wool	Cotton	Nylon
Sorption Regain (90% R.H., 15°C.), g.H_2O/kg. fiber	275	237	130	69
Desorption Regain (33.5% R.H., 30°C.), g.H_2O/kg. fiber	98	105	69	20
Net Water Gain (33.5% R.H., 30°C., to 90% R.H., 15°C.), g.H_2O/kg. fiber	177	132	61	49
Heat of Wetting, Q (33.5 to 90% R.H., 25°C.), cal/g.H_2O	8.0	7.2	3.5	1.8
Heat of Condensation, L (22.5°C.), cal/g.H_2O	584	584	584	584
Unit Heat of Sorption, L + Q, cal/g.H_2O	592	591	588	586
Total Heat of Sorption (33.5% R.H., 30°C. to 90% R.H., 15°C.), kilocal/kg. fiber	105	78	36	29

TABLE 6, REPORT 18

TEMPERATURE RISE EFFECTS IN FABRIC ASSEMBLIES DUE TO CHANGE IN TEMPERATURE AND RELATIVE HUMIDITY

Run	Assembly Examined[a]	Initial Conditions		Final Conditions			Extent of Temperature Effect[b]
		Temp.	R.H.	Temp.	R.H.	Wind	
R_2	Wool serge & underwear	21°C.	0%	0°C.	70%	none	Both runs similar
	Wool serge & underwear	21°C.	40%	0°C.	70%	none	
R_4	Napped Orlon serge & underwear, nap inside	21°C.	0%	0°C.	66%	none	1.5°C. higher than reference
	Napped Orlon serge & underwear, nap outside	21°C.	0%	0°C.	66%	none	
R_7	Wool serge & underwear	35°C.	0%	21°C.	65%	5 mph	1.5°C. higher than reference
	Orlon serge & underwear	35°C.	0%	21°C.	65%	5 mph	
W248 to W253	Wool serge placed on sweating skin	35°C.	20%	30°C.	100%	15 mph	4°C. rise over reference for 7 min.
	Orlon serge placed on sweating skin	35°C.	20%	30°C.	100%	15 mph	
R_{11}	Sheared wool serge & underwear	32°C.	20%	32°C.	9?%	8 mph	12°C. rise, 24 min.[c]
	Orlon serge & underwear	32°C.	20%	32°C.	90%	8 mph	4°C. rise, 10 min.
R_{12}	Sheared wool serge & underwear	32°C.	0%	32°C.	87%	8 mph	12°C. rise, 24 min.
	Orlon serge & underwear	32°C.	0%	32°C.	87%	8 mph	6°C. rise, 14 min.

a Wool underwear used in two layer experiments.
b Temperature rise in the first compared with the second of the pair.
c Temperature rise in the peak above ambient condition and time given is the half time of the cooling curve to equilibrium temperature.

TABLE 7, REPORT 18

CALCULATION OF THE WATER VAPOR RESISTANCE OF A STANDARD
FOUR LAYER COLD WEATHER ASSEMBLY[a]

Insulating Layer	Water Vapor Resistance cm of air
Underwear	0.12
Serge	0.23
Oxford	0.18
Sateen	0.17
Air Layers	0.70
Total	1.40

[a] From data of Whelan et al, T.R.J., 25, 197 (1955).
Values are also given for cellophane (1.3 cm)
and nylon film (8.5 cm).

TABLE 8, REPORT 18

MOISTURE TRANSMISSION AND EVAPORATIVE COOLING IN
A STANDARD FOUR LAYER COLD WEATHER ASSEMBLY

Metabolic output - 420 kcal/m^2hr.

Observed surface temperatures - inside 30°C., outside -5°C.

Water vapor pressure differential - 28.66 mm of Hg

Total water transfer - 1.61 x 10^{-3} g/cm^2 sec.

Theoretical Maximum[a] cooling from evaporation - 350 kcal/m^2/hr.

Estimated Fraction[b] for direct skin cooling - 85 kcal/m^2/hr

[a] This corresponds to all the water leaving the sweating skin.
[b] That portion of the cooling which affects the skin directly -
     estimated from the temperature gradients through the fabric layers.

TABLE 9, REPORT 18

THE EFFECT OF SURFACE COVERAGE
ON THE WATER LOSS FROM A SWEATING SKIN[a]
(Wind Velocity 15 mph, Ambient Temperature 7°C. below Skin Temperature)

Coverage with a Serge Fabric %	Moisture Loss[b] g/cm hr	Theoretical Cooling Value[c] kcal/m²/hr
100	2.4	145
95	3.4	205

[a] In these experiments a single layer of wool serge fabric was placed on a simulated sweating arm with skin surface coverage as shown. Water loss from the arm was obtained by weighing (see Warm Wind Tunnel Technique, Report 5, Project QM564).

[b] Calculated for unit vapor pressure difference between the sweating surface and the ambient air for a cell of area $2.72 \times 10^{-2}m^2$.

[c] Calculated for an ambient temperature of 28°C. and based on evaporation of all the water.

TABLE 10, REPORT 18

EFFECTS OF WATER VAPOR IMPERMEABLE
LAYERS IN VARIOUS COLD WEATHER ENSEMBLES

1. Sleeping Bags

Climatic Research Laboratory Provisional Reports, March 13, 1944 and
March 23, 1944.

Subjective tests on the insulation afforded by sleeping with a water vapo:
impermeable layer on both inside and outside showed a significant increase in
tolerance time for men testing the inside case. At the same time it was
observed that the moisture transfer to the sleeping bag was identical in
the cases in which either a vapor permeable or vapor impermeable outer
case was used.

2. Field Trouser Tests

Climatic Research Laboratory Provisional Reports, August 4 and August 5, 1944.

In these tests the heat load, tolerance time, and skin temperatures of
soldiers marching in the cold followed by periods of rest were examined.
The heat load and tolerance times were found not to be difference when im-
permeable or permeable pants were worn over the standard wool serge trousers.

3. Vapor Barrier Sockgear

Climatic Research Laboratory Provisional Reports, June 24 and July 4, 1944.

Tolerance times and skin temperatures of men with and without vapor
sockgear were determined at rest after a hike in the cold. The vapor barrier
was substantially effective in increasing tolerance times and toe temperatures.

TABLE 11, REPORT 18

HEAT DISSIPATING CAPACITY AND INSULATION OF FOUR
LAYER COLD WEATHER ASSEMBLIES CONTAINING A WATER VAPOR IMPERMEABLE
MEMBRANE OF VARIABLE SIZE NEXT TO THE UNDERWEAR LAYER

(Wind Velocity 19 mph)

Coverage with Impermeable Layer %	Relative Heat Dissipating Capacity[a] %	Relative Overall Thermal Resistance[b] %
73	95	143
87	90	155
93	84	170
100	76	190

[a] At high metabolic conditions and relative to the value with no impermeable layer.

[b] Under low metabolic conditions and relative to the value with no impermeable layer.
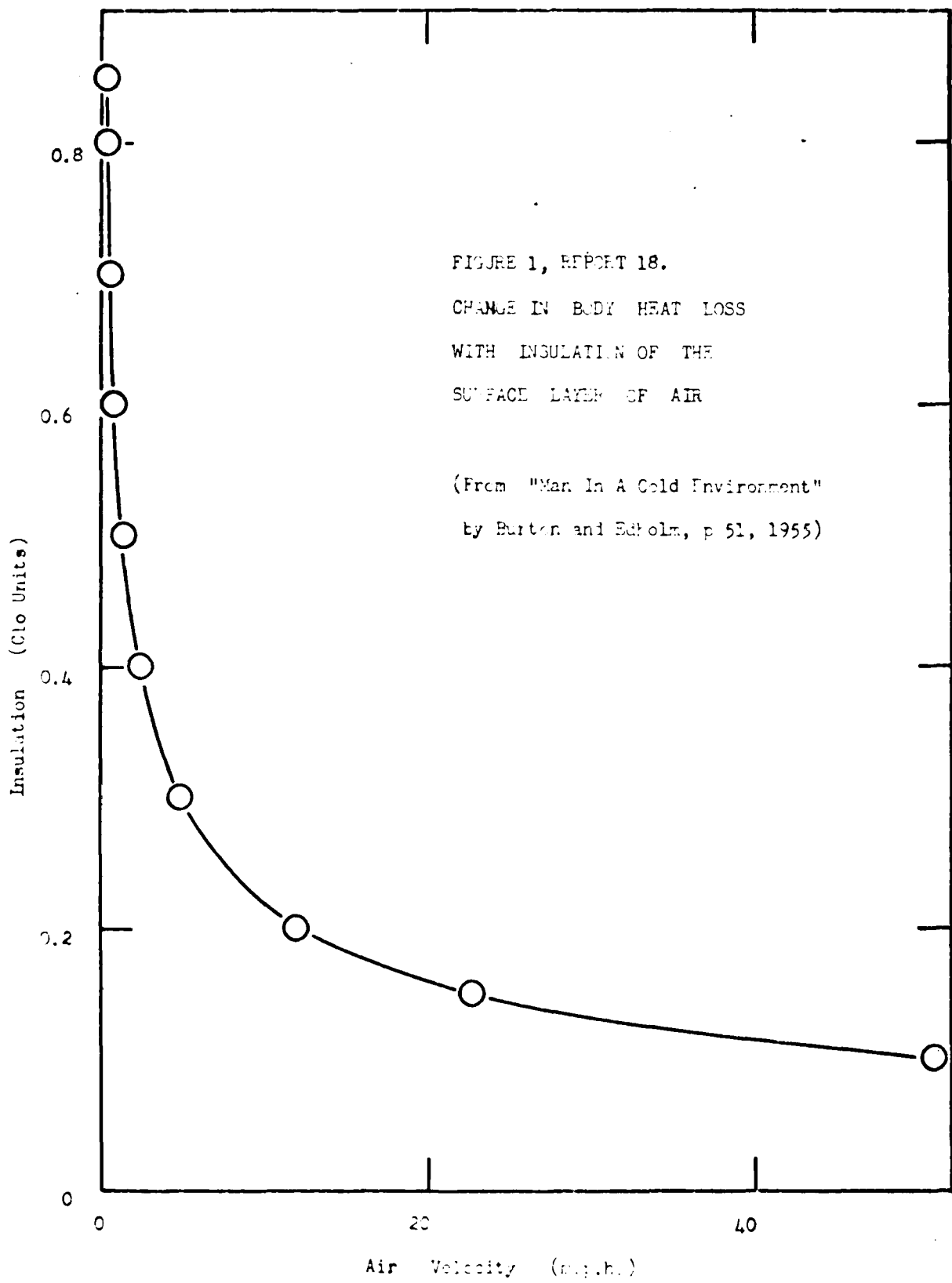
TABLE 12, REPORT 18

MOISTURE TRANSFER BETWEEN DRY SERGE AND
WET UNDERWEAR FABRICS PARTIALLY SEPARATED BY
A VAPOR IMPERMEABLE MEMBRANE

Contact Pressure 0.1 lb/in^2

Underwear Moisture %	Contact Time min.	Serge Condition[a]	Moisture Gain[b]	
			Without Membrane %	With Membrane %
100	10	non-wettable	6.3	0.1
		wettable	7.3	0.2
	60	non-wettable	23.4	0.3
		wettable	28.0	1.2
175	10	non-wettable	8.6	0.3
		wettable	32.7	0.4
	60	non-wettable	27.0	0.4
		wettable	46.4	8.8

[a] The same wool serge in one case made wettable by treatment with 0.1% non-ionic detergent.

[b] Weight gain above conditioned weight at 70°F. and 65% R.H.

FIGURE 1, REPORT 18.

CHANGE IN BODY HEAT LOSS
WITH INSULATION OF THE
SURFACE LAYER OF AIR

(From "Man In A Cold Environment"
by Burton and Edholm, p 51, 1955)

FIGURE 2, REPORT 18.

INSULATION OF COLD WEATHER

FABRICS AS A FUNCTION OF

THICKNESS

(From Ph.D Thesis by
M.A.Morris, Univ.of
Minnesota, 1955)

Multiple Fabric Layers

Single Fabric Layers

FIGURE 3, REPORT 18.

Thermal Resistance of a Four
Layer Cold Weather Assembly as
a Function of Exposure Time to
Heavy Sweating Conditions

Exposure Time to Sweating Conditions (minutes)
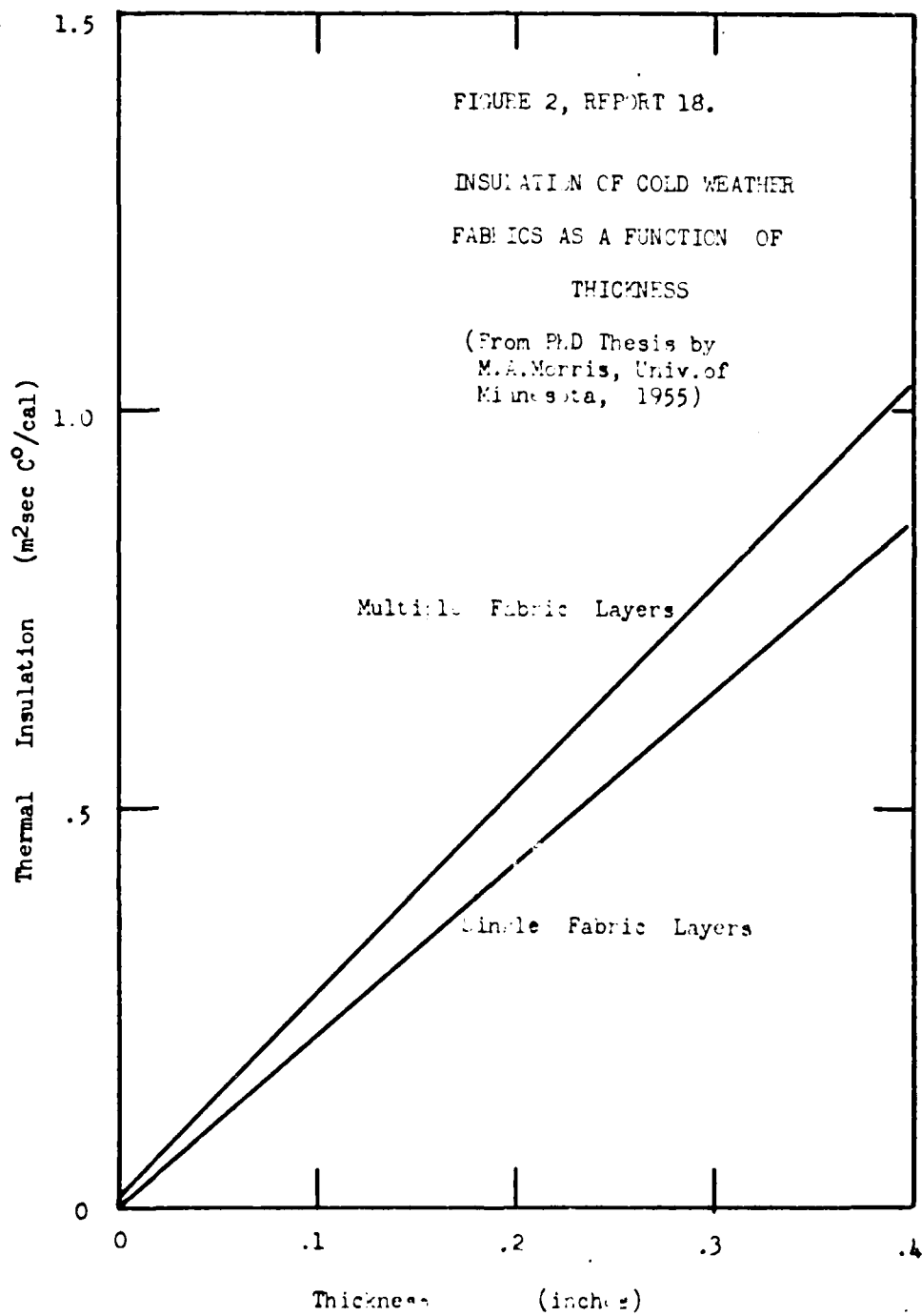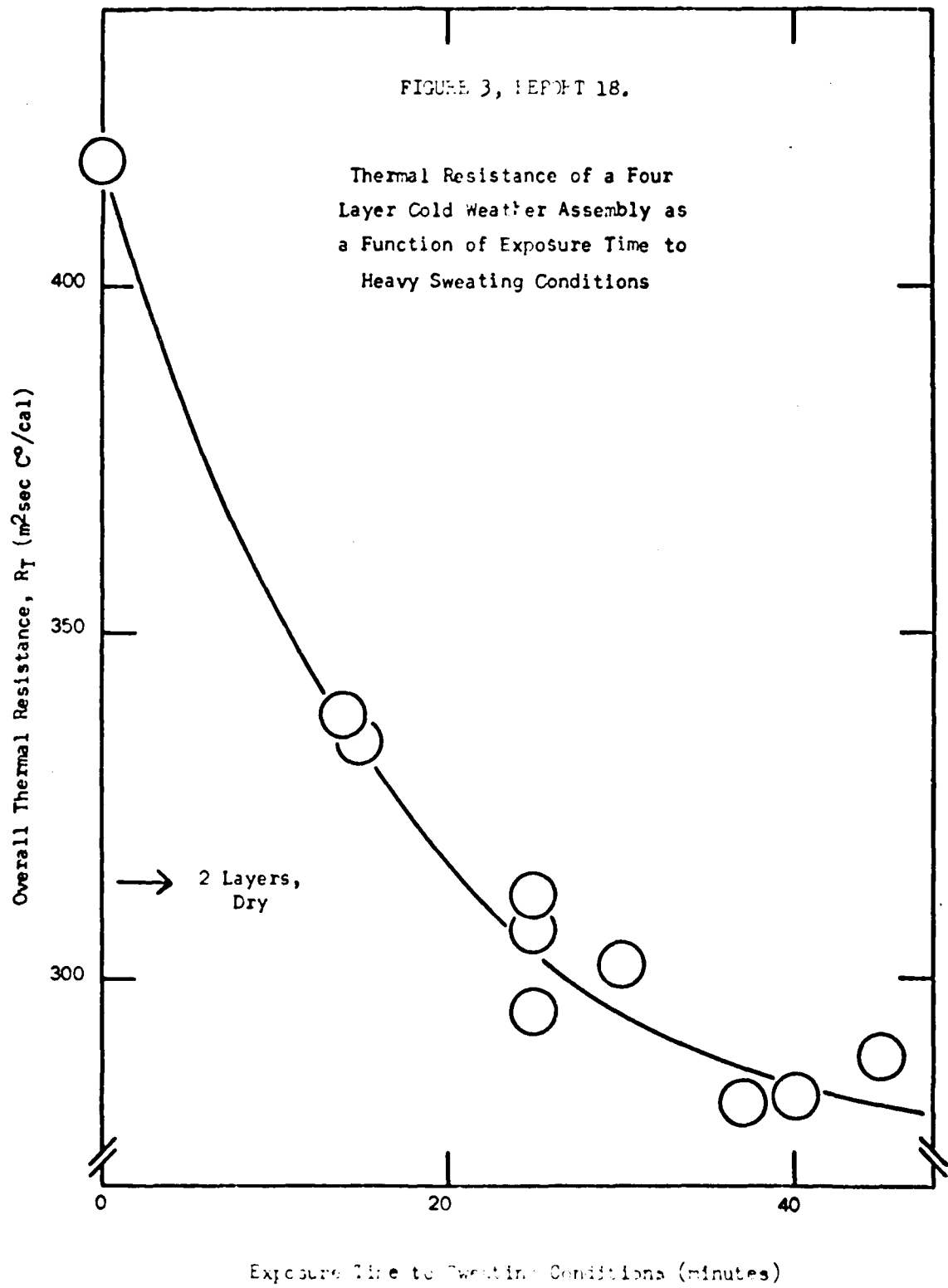
Figure 4, Report 18. The Heat of Moisture Regain: Temperature Rise in Double Fabric Layers, Top Layer Serge, Bottom Layer Wool Underwear

Initial Conditions 32°C, 0% R.H.
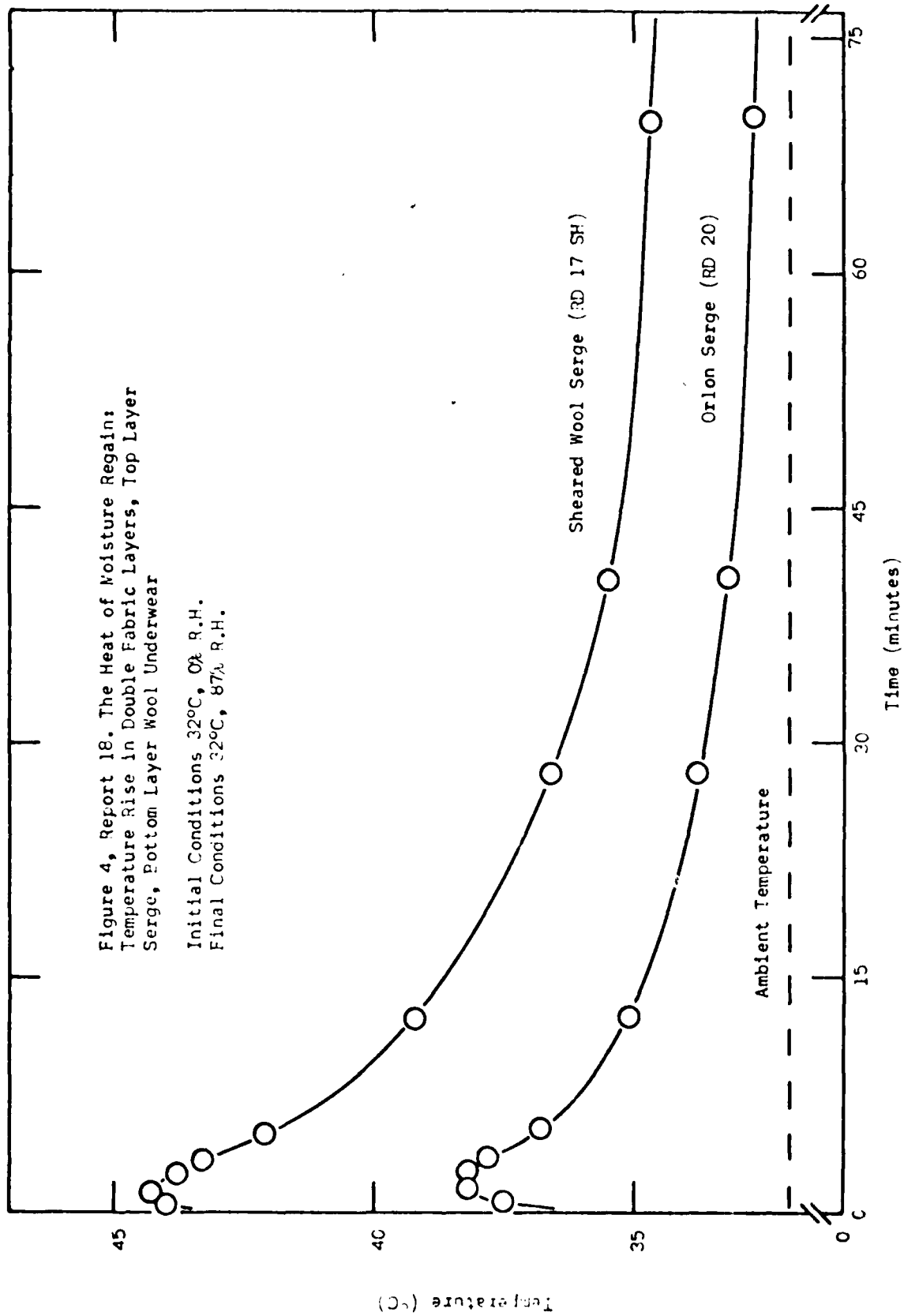Final Conditions 32°C, 87% R.H.

Figure 5, Report 18. Moisture Distribution in Four Layer Cold Weather Assemblies
(Bar width proportional to fabric thickness)
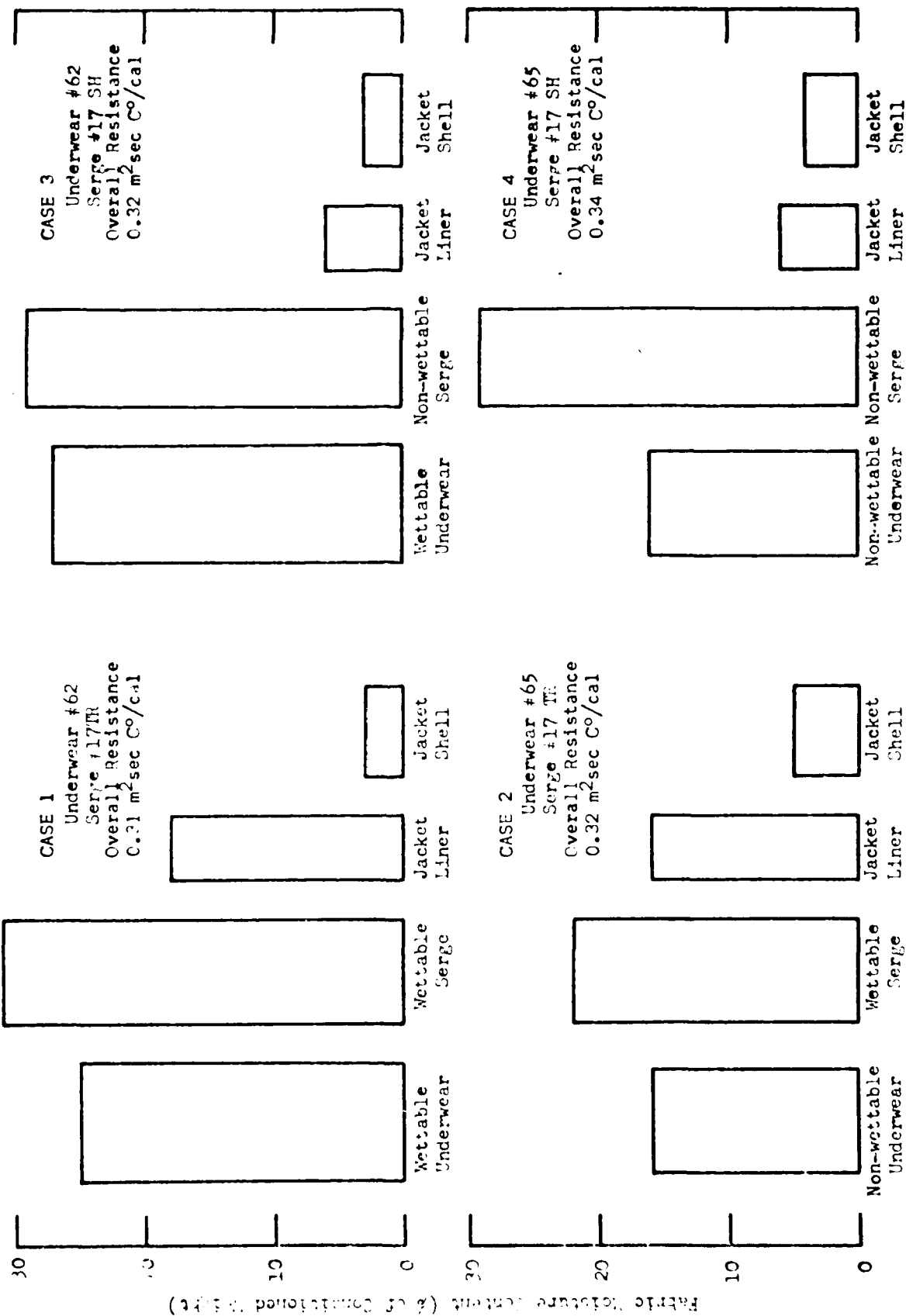Wind Velocity = 12 mph

Figure 4. Report 1b. Moisture Distribution in a Four Layer Cold Weather Assembly as a Function of the Position of an Impermeable Layer

Wind Velocity = 12 mph

First Layer - wettable nylon underwear #62
Second Layer - non-wettable serge #17 SH
Third and Fourth Layers - field jacket

Position of impermeable layer indicated by dashed line.
Bar width proportional to fabric thickness.

CASE 1
Overall Resistance
0.53 m² sec C°/cal

CASE 2
Overall Resistance
0.41 m² sec C°/cal

CASE 3
Overall Resistance
0.33 m² sec C°/cal

CASE 4
Overall Resistance
0.32 m² sec C°/cal

Fabric Moisture Content (% of conditioned weight)

FIGURE 7, REPORT 18.

RELATIVE HEAT STRESS FOR

COLD - WET UNIFORMS

(From E.P.R.
Study 5219-C
6/30/53)

Pulse (beats/minute)

150   130   110   90

Sweat loss (grams)

1200   800   400   0

Coldbar   Standard   Coldbar, 1/8" holes